New product development using experimental design

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SOM Theme A: Intra-Firm Coordination and Change

Abstract

New product development is one of the most powerful but difficult activities in business. It is also a very important factor affecting final product quality. There are many techniques available for new product development. Experimental design is now regarded as one of the most significant techniques. In this article, we will discuss how to use the technique of experimental design in developing a new product - an extrusion press. In order to provide a better understanding of this specific process, a brief description of the extrusion press is presented. To ensure the successful development of the extrusion press, customer requirements and expectations were obtained by detailed market research. The critical and non-critical factors affecting the performance of the extrusion press were identified in preliminary experiments. Through conducting single factorial experiments, the critical factorial levels were determined. The relationships between the performance indexes of the extrusion press and the four critical factors were determined on the basis of multi-factorial experiments. The mathematical models for the performance of the extrusion press were established according to a central composite rotatable design. The best combination of the four critical factors and the optimum performance indexes were determined by optimum design. The results were verified by conducting a confirmatory experiment. Finally, a number of conclusions became evident.

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1. Introduction

New product development is one of the most powerful but difficult activities in business (Clark and Wheelwright, 1995). Business managers and marketing academics alike agree that an essential element of an organization's long-term survival is success in new product development (Henry et al., 1989). The development of outstanding products not only opens new markets and attracts new customers, but also leverages existing assets and enlarges an organization's capabilities. Product development has a very important impact on final product quality. Many researchers and practitioners discuss the importance of product development. Juran and Gryna (1993) suggest that 40 percent of mechanical and electronic products of at least moderate complexity experience fitness-for-use problems as a result of errors during product development. Flynn et al. (1994) report that sound product development allows a business to meet or exceed the needs and desires of customers better than its competitors, and, therefore, to increase its market share. In fact, product development may be related to all of Garvin's (1987) critical dimensions of product quality: performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality.

Product development translates the functional needs and expectations of a customer into specific engineering and quality characteristics (Juran and Gryna, 1993). The typical phases of new product development include concept development (product architecture, conceptual design, target market), product planning (model building, small-scale testing, investment), product/process engineering (detailed design of product and tools/equipment, building/testing prototypes), pilot production/ramp-up (volume production prove out, factory start-up, volume increases to commercial targets) (Wheelwright and Clark, 1992). There are many factors affecting the success of new product development. Six keys are management of the development process, design, conjoint and related analysis techniques, pretest-market models, new-product-diffusion models, and consumer-behavior models (Henry et al., 1989). For traditional and simple products, the developmental process is not complicated and can be achieved by experienced engineers without using any special techniques. For modern products, it is impossible to reach the development target without using suitable techniques (Juran and Gryna, 1993). There are several important methods or techniques that can be used in product development, such as experimental design, concurrent engineering, reliability engineering, designing for manufacturability, quality function deployment, value engineering, computer-aided design (Zhang, 1997). In this article, only the technique of experimental design is addressed.

Experimental design was developed by R.A.Fisher in England in the 1920s (Logothetis and Wynn, 1989). At that time, experimental design was mainly used in agricultural research. It was not until the early 1950s when experimental design began to be used widely in technological studies that its progress and development were very rapid (Logothetis and Wynn, 1989). Nowadays, experimental design has been used in various industries for process improvement and product development. It is widely regarded as one of the most significant techniques used for new product development. Blake et al. (1994) state that “experimental design is a strategic weapon to battle competitors worldwide by designing robust products, reducing time to market, improving quality and reliability, and reducing life-cycle cost”. The main advantage for adopting experimental design in new product development is to obtain an amazing amount of information about a new product using a limited number of experimental runs. Through analyzing the information obtained from experimental design, various parameters relating to a new product can be easily and accurately determined. The main steps for using experimental design in new product development can be summarized as follows:

- identifying factors which may influence the performance of a new product;
- selecting appropriate factorial levels;
- choosing the matrix of experimental design;
- conducting experiments and collecting experimental data;
- analyzing experimental data;
- determining optimum factorial values;
- verifying the validity of optimum factorial values.

Many researchers and practitioners discuss how to use experimental design in practice. Lim (1990) examines the ways to improve quality using experimental design. Lochner and Matar (1990), Logothetis and Wynn (1989) also discuss how to use experimental design for product development in their books. However, there is in fact a gap between the technique of experimental design and its practical application. One example is that: the awareness, knowledge, and use of experimental design are very poor even in one of the world's largest and most successful companies (Carlsson, 1996). In such a context, it is not surprising that some designers still have difficulties in using experimental design in practice. In order to bridge the gap and provide a better understanding of using this technique, this article mainly examines how to use experimental design in developing a new product - an extrusion press. The detailed process will be found throughout this article. Through the approach of using experimental design in developing the extrusion press, a number of conclusions have been formulated.

Section 2 presents a brief description of the extrusion press. In Section 3, customer requirements and expectations are presented. In Section 4, the critical factors and the factorial levels are identified. Section 5 presents the detailed design of experiments. The mathematical models for the extrusion press performance are discussed in Section 6. Section 7 describes how to use optimum design to calculate the optimum results. Section 8 provides a number of conclusions for this article.

2. A Brief Description of the Extrusion Press

Various extrusion presses have been widely used in such different industries as the plastics and the food industries. The extrusion press discussed in this article is the specially developed one which is used for processing granulated fish feed. Figure 1 shows a simplified structure of the extrusion press. The principle of the extrusion press is fairly straightforward. Raw materials (feed-stuff) are extruded through very small holes in a pattern plate by using an instrument with a screw inside a sleeve to push materials out. Next to the pattern plate is a cutting tool that cuts the filiform materials coming out of the holes into granulated fish feed. The extrusion press's essential components are, therefore, a screw, a pattern plate, a sleeve, a frame, and a cutting tool. All of these factors have to be taken into account when developing the extrusion press.

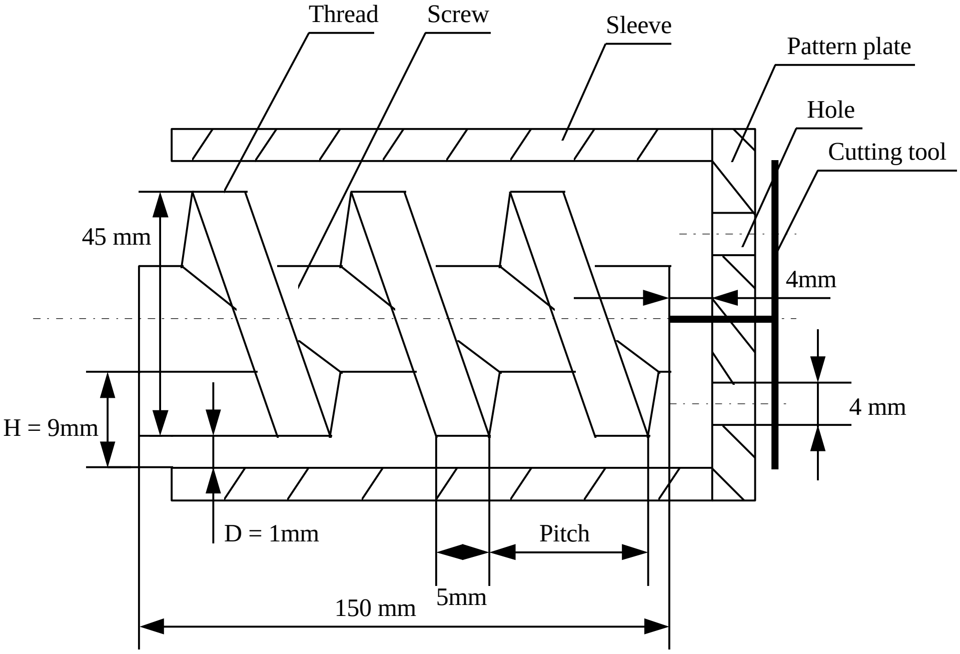

Figure 1. Structure of the Extrusion Press

3. Customer Requirements and Expectations

Deming defines quality as a product's ability, not merely to meet a customer's expectations, but to exceed them. Deming's philosophy starts and finishes with the customer (Deming, 1986). There are many researchers that talk about the importance of putting the customer first in every decision made, especially at product development stage. Customer needs should be taken into account during the whole process of product development, then there is less probability of quality problems once full production begins (Flynn et al., 1994). The ultimate measure of new products is customer satisfaction, which may very well predict their future market success or failure. Consequently, products have to be developed and produced in such a manner that customer requirements and expectations are fully met. Product development is responsible for designing new products which meet customer requirements and expectations and which can be consistently and economically produced by manufacturing.

According to the principles proposed by these practitioners, the first steps in the successful development of the extrusion press involved the determination of customer requirements and expectations and their subsequent translation into product quality characteristics. Thus, it was very important to evaluate customer satisfaction and customer perception about the performance of the extrusion press. The insights gained clearly helped the designers to improve the extrusion press's design. The extrusion press is used for processing granulated fish feed. Farmers are its potential users. Some potential users were investigated in order to obtain their requirements, expectations, and perceptions about the extrusion press. Through this detailed market research, the customer requirements and expectations are defined as follows:

- Performance or the primary operating characteristics of the extrusion press. There are three main parameters. The first is the quantity of granulated fish feed that the extrusion press can produce per kilo-watt hour. The potential users expect the extrusion press to produce more granulated fish feed with lower electricity consumption. This feature is the most important among all the characteristics of the extrusion press. The second parameter is the quality of granulated fish feed. Granulated fish feed is used by farmers who raise fish. When granulated fish feed is thrown into water, farmers expect that more than half of the feed granules will float on the surface and less than half of the feed granules sink to the bottom. This expectation is the second most important characteristic for the extrusion press. The third performance parameter involves the quantity of granulated fish feed that can be produced within a specified time period. This is the third most important characteristic for the extrusion press.
- Availability. The potential users expect the extrusion press to be powered by 220- voltage electricity. A smaller than 2 kilo-watt electric motor is preferred.
- Maintenance. This is also an important attribute of the extrusion press. The potential users expect the extrusion press should be easy to repair.
- Reliability. This characteristic refers to the press's ability to function without problems for a specified time period. In this case the potential users expect the

extrusion press should remain in good condition without failing for at least one year. The reliability mainly depends on the complexity of the extrusion press, the nature of its components, its environmental conditions, and its working time per day.

- Durability. This reflects both the economic and technical factors of the extrusion press. The potential buyers expect it to have a long service life before deterioration begins to set in.
- Cost. The potential users expect the extrusion press to have a low price so that they can afford to buy it.

Based on the market research, there are many requirements and expectations from the potential customers, all of which have to be taken into account in product development. However, in this article, only the three main performance parameters, the output per kilo-watt hour, the floatation rate, and the output per hour, are addressed. The need to maximize output per kilo-watt hour, to achieve a more than or equal to 50 percent floatation rate, and to ensure a high output per hour motivates the designers to use experimental design in product development. Although the structure of the extrusion press is not complex, there are still many factors affecting its performance. It is difficult to know which factors affect performance indexes on what values to set for each factor. Experiments may be performed to determine appropriate factors and factorial levels. A simple experimental design is the full-factorial design, which consists of all possible combinations of the factors and factorial levels. The problem with a full-factorial design is that, for most practical situations, it is too costly and almost impossible. In order to determine the values of each factor easily and accurately, the technique of experimental design fits this purpose. The detailed process of using experimental design will be found in the following Sections.

4. Identifying Critical Factors and Levels

There are many factors affecting the performance of the extrusion press. Some are critical factors and others are non-critical factors. In order to conduct experimental design effectively, the critical factors should be determined.

4.1 Determining Critical Factors

An important part of planning a factorial experiment is the identification of the factors which affect the performance of the extrusion press. For this purpose, brainstorming sessions and preliminary experiments were organized for identifying the factors affecting the performance. The critical factors were then identified by eliminating the unimportant factors. The factors which may affect the performance of the extrusion press are:

- the turning-speed of the screw;
- the pitch of the screw;
- the moisture content of raw materials (feed-stuff);
- the number of holes in the pattern plate;
- the length of the screw;
- the shape of the pattern plate;
- the inside surface shape of the sleeve;
- the width of the thread;
- the clearance between top thread surface and inside surface of the sleeve;
- the distance between bottom surface of the screw and inside surface of the sleeve;
- the cutting tool.

These factors were taken into account when developing the extrusion press. In order to determine the critical factors affecting the performance of the extrusion press, some preliminary experiments were conducted. Based on the results of preliminary experiments, some critical and non-critical factors were determined. The critical factors are the turning-speed of the screw, the pitch of the screw, the moisture content of raw materials, and the number of holes in the pattern plate. The others are non-critical factors. The detailed preliminary experimental results are not shown here, but some values of the non-critical factors are shown in Figure 1.

4.2 Determining Factorial Levels

The critical factors were identified on the basis of preliminary experiments. In order to determine the detailed values of the four critical factors, multi-factorial experiments would be conducted. At this stage, the next step was to determine the values of each factorial level. Based on the preliminary experiments and the designers' knowledge in this subject, the values of each factorial level were determined and which are listed in Table 1.

Table 1. The Levels for the Four Critical Factors

Turning-speed (r/min)	140	240	340	440	540
Screw pitch (mm)	10	14	18	22	26
Moisture content (%)	12	15	18	21	24
Number of holes	2	3	4	5	6

In this experimental design, there are four factors and each factor has five levels. In order to confirm whether the selected factorial levels were suitable in practice, a single factorial experimentation method was used, i.e., the "change-one-factor-at-a-time" method. It was to vary only one factor from one level to another level, while keeping all the other factors fixed. The single factorial experiments continued until each factorial level had changed once, while everything else was kept constant. This method was used to confirm the selected levels of the four critical factors.

Turning-Speed

When the screw pitch is 18 mm long, the moisture content of raw materials 18 percent, the number of holes in the pattern plate 4 (diameter is 4 mm), and other factors held constant, the performance indexes affected by turning-speed are tabulated in Table 2. When the turning-speed is more than 540 r/min, the extrusion press consumes more energy and a high-power electric motor is required. Because the potential users of the extrusion press are farmers living in rural areas, they can only use civil electricity for driving electric motor. With the limitations resulting from the electrified wire netting, an electric motor should be less than 2 kilo-watts. So in this experimental design, the highest turning-speed is 540 r/min. When the turning-speed is less than 140 r/min, the extrusion press is not working efficiently and effectively. In addition, the output per kilo-watt hour is too low. Therefore, the lowest level for the turning-speed is selected as 140 r/min.

Table 2. Performance Indexes Affected by Turning-Speed

Turning-speed (r/min)	140	240	340	440	540
Output (kg/kwh)	3.113	4.698	5.415	5.602	5.891
Floatation rate (%)	51	62	84	64	52
Output (kg/h)	2.83	9.23	14.35	18.56	22.22

Screw Pitch

When the turning-speed is 340 r/min, the moisture content of raw materials 18 percent, the number of holes 4 (diameter is 4 mm), and other factors held constant, Table 3 shows the performance indexes for the extrusion press. When the screw pitch is more than 26 mm, the value of the floatation rate is less than 50 percent and the quality of granulated fish feed does not meet the requirements and expectations of the potential users. When the screw pitch is less than 10 mm, the overall performance indexes are too low. As a result, the highest and lowest level in this experimental design for the screw pitch is 26 and 10 mm respectively.

Table 3. Performance Indexes Affected by Screw Pitch

Screw pitch (mm)	10	14	18	22	26
Output (kg/kwh)	3.901	4.443	5.304	5.522	5.943
Floatation rate (%)	0	46	80	50	35
Output (kg/h)	5.91	10.84	12.96	13.64	14.11

Moisture Content

When the turning-speed is 340 r/min, the screw pitch 18 mm, the number of holes 4 (diameter is 4 mm), and other factors held constant, the performance indexes of the extrusion press are showed in Table 4. When the moisture content is equal to 24 percent, the value of the floatation rate is equal to 50 percent. When the moisture content is more than 24 percent, the value of the floatation rate is less than 50 percent. In addition, because of high moisture content, the flow of raw materials is poor. When the moisture content is less than or equal to 12 percent, the output per kilo-watt hour is too low. Consequently, the highest and lowest level for the moisture content in this experimental design are 24 and 12 percent respectively.

Table 4. Performance Indexes Affected by Moisture Content

Moisture content (%)	12	15	18	21	24
Output (kg/kwh)	3.897	5.262	5.852	6.751	7.328
Floatation rate (%)	96	92	84	80	50
Output (kg/h)	13.33	13.77	14.51	13.87	13.04

Number of Holes

When the turning-speed is 340 r/min, the screw pitch 18 mm, the moisture content of raw materials 18 percent, and other factors held constant, the performance indexes of the extrusion press are shown in Table 5. When the number of holes is equal to 6, the floatation rate is equal to 30 percent. When the number of holes is less than or equal to 2, the output per kilo-watt hour is too low. Therefore, the highest and lowest number of holes in this experimental design are 6 and 2 respectively.

Table 5. Performance Indexes Affected by Number of Holes

Number of Holes	2	3	4	5	6
Output (kg/kwh)	4.353	5.361	5.563	5.753	5.907
Floatation rate (%)	97	88	82	58	30
Output (kg/h)	12.86	13.74	13.93	14.63	16.37

Through conducting the single factorial experiments, it was concluded that the selected factorial levels of the four critical factors were suitable.

5. Determining Experimental Design

In order to determine the values of the four critical factors and pursue the optimum performance indexes, an appropriate matrix of experimental design should be selected. The relationships between the performance indexes of the extrusion press and the four critical factors can be determined on the basis of multi-factorial experiments.

5.1 Coding for Factors and Levels

Based on the single factorial experiments, the factorial levels of the four critical factors were identified. Table 6 lists the coding names for each factor and its factorial levels.

Table 6. Coding Names for Factors and Factorial Levels

Coding names	Factors	-2	-1	0	+1	+2	Interval
X_1	Turning-speed (r/min)	140	240	340	440	540	100
X_2	Screw pitch (mm)	10	14	18	22	26	4
X_3	Moisture content (%)	12	15	18	21	24	3
X_4	Number of holes	2	3	4	5	6	1

5.2 Selecting Matrix of Experimental Design

In order to effectively conduct the experiments, a central composite rotatable design (Xiao and Zhong, 1985; Barker, 1985; Belz, 1973) was adopted on the basis of the above analysis. The matrix is shown in Table 7.

Table 7. Matrix of a Central Composite Rotatable Design

No.	X0	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14
						X1X2	X1X3	X1X4	X2X3	X2X4	X3X4	X1X1	X2X2	X3X3	X4X4
												-.6667	-.6667	-.6667	-.6667
1	1	-1	-1	-1	-1	1	1	1	1	1	1	.3333	.3333	.3333	.3333
2	1	1	-1	-1	-1	-1	-1	-1	1	1	1	.3333	.3333	.3333	.3333
3	1	-1	1	-1	-1	-1	1	1	-1	-1	1	.3333	.3333	.3333	.3333
4	1	1	1	-1	-1	1	-1	-1	-1	-1	1	.3333	.3333	.3333	.3333
5	1	-1	-1	1	-1	1	-1	1	-1	1	-1	.3333	.3333	.3333	.3333
6	1	1	-1	1	-1	-1	1	-1	-1	1	-1	.3333	.3333	.3333	.3333
7	1	-1	1	1	-1	-1	-1	1	1	-1	-1	.3333	.3333	.3333	.3333
8	1	1	1	1	-1	1	1	-1	1	-1	-1	.3333	.3333	.3333	.3333
9	1	-1	-1	-1	1	1	1	-1	1	-1	-1	.3333	.3333	.3333	.3333
10	1	1	-1	-1	1	-1	-1	1	1	-1	-1	.3333	.3333	.3333	.3333
11	1	-1	1	-1	1	-1	1	-1	-1	1	-1	.3333	.3333	.3333	.3333
12	1	1	1	-1	1	1	-1	1	-1	1	-1	.3333	.3333	.3333	.3333
13	1	-1	-1	1	1	1	-1	-1	-1	-1	1	.3333	.3333	.3333	.3333
14	1	1	-1	1	1	-1	1	1	-1	-1	1	.3333	.3333	.3333	.3333
15	1	-1	1	1	1	-1	-1	-1	1	1	1	.3333	.3333	.3333	.3333
16	1	1	1	1	1	1	1	1	1	1	1	.3333	.3333	.3333	.3333
17	1	-2	0	0	0	0	0	0	0	0	0	3.3333	-.6667	-.6667	-.6667
18	1	2	0	0	0	0	0	0	0	0	0	3.3333	-.6667	-.6667	-.6667
19	1	0	-2	0	0	0	0	0	0	0	0	-.6667	3.3333	-.6667	-.6667
20	1	0	2	0	0	0	0	0	0	0	0	-.6667	3.3333	-.6667	-.6667
21	1	0	0	-2	0	0	0	0	0	0	0	-.6667	-.6667	3.3333	-.6667
22	1	0	0	2	0	0	0	0	0	0	0	-.6667	-.6667	3.3333	-.6667
23	1	0	0	0	-2	0	0	0	0	0	0	-.6667	-.6667	-.6667	3.3333
24	1	0	0	0	2	0	0	0	0	0	0	-.6667	-.6667	-.6667	3.3333
25	1	0	0	0	0	0	0	0	0	0	0	-.6667	-.6667	-.6667	-.6667
26	1	0	0	0	0	0	0	0	0	0	0	-.6667	-.6667	-.6667	-.6667
27	1	0	0	0	0	0	0	0	0	0	0	-.6667	-.6667	-.6667	-.6667
28	1	0	0	0	0	0	0	0	0	0	0	-.6667	-.6667	-.6667	-.6667
29	1	0	0	0	0	0	0	0	0	0	0	-.6667	-.6667	-.6667	-.6667
30	1	0	0	0	0	0	0	0	0	0	0	-.6667	-.6667	-.6667	-.6667
31	1	0	0	0	0	0	0	0	0	0	0	-.6667	-.6667	-.6667	-.6667
32	1	0	0	0	0	0	0	0	0	0	0	-.6667	-.6667	-.6667	-.6667
33	1	0	0	0	0	0	0	0	0	0	0	-.6667	-.6667	-.6667	-.6667
34	1	0	0	0	0	0	0	0	0	0	0	-.6667	-.6667	-.6667	-.6667
35	1	0	0	0	0	0	0	0	0	0	0	-.6667	-.6667	-.6667	-.6667
36	1	0	0	0	0	0	0	0	0	0	0	-.6667	-.6667	-.6667	-.6667

The first column is the number of experimental runs. The second column (x_0) is constant. From the third column to the sixth column (x_1, x_2, x_3, x_4), every column represents a factor, every row represents an experimental trial, and entries from the third column to the sixth column in the matrix represent the factorial levels (x_1, x_2, x_3, x_4). From the seventh to the twelfth column (x_5, x_6, x_7, x_8 x_9, x_{10}), each represents the interaction between the relevant two factors. From the thirteenth to the sixteenth column (x_{11}, x_{12}, x_{13}, x_{14}), each one is quadratic.

There are some general rules for conducting experiments. Firstly, the full experiments were run in a random sequence. The reason for randomization is to avoid having the tests ruined by time or sequence-related variables. It is important for the validity of the experiments that the experiments are run in a random order. If the experiments were run in the order listed in Table 7, then unsuspected factors which changed with time might distort the analysis and provide misleading conclusions. Secondly, Table 7 indicates that 36 experiments are needed. In order to ensure the accuracy of experimental results, two experiments for each set of conditions were run. The aim of duplicate experiments is to reduce experimental errors. The effects of high variability on experimental results can often be reduced by repeating the experiment. Average values have less variability than individual measurements, so the calculated averages tend to be closer to true factorial effects. Without replications, a single erroneous or unusual sample value may distort the whole analysis. Thirdly, data were measured after the extrusion press was operating for a half hour. Under such a condition, the extrusion press was functioning normally. After all the experiments had been run, the average performance indexes of the extrusion press were obtained. These performance indexes are tabulated in Table 8.

Table 8. Performance Indexes

Trial No.	Output (kg/kwh)	Floatation rate(%)	Output (kg/h)	Trial No.	Output (kg/kwh)	Floatation rate(%)	Output (kg/h)
1	3.572	96	5.898	19	3.760	0	5.696
2	4.031	88	10.714	20	5.959	16	13.740
3	4.530	88	9.836	21	4.283	98	14.061
4	4.728	94	15.000	22	7.124	45	13.044
5	4.246	90	5.000	23	5.203	98	13.845
6	4.532	75	9.999	24	5.406	32	15.385
7	4.973	82	8.912	25	6.050	82	15.125
8	5.866	92	14.172	26	5.581	88	14.400
9	4.144	10	4.973	27	6.253	78	15.789
10	4.819	74	14.062	28	5.838	86	13.550
11	4.687	26	8.612	29	5.709	90	12.590
12	5.128	82	15.384	30	5.656	96	14.636
13	4.379	4	4.762	31	5.397	66	14.286
14	5.556	72	12.857	32	5.231	95	15.921
15	5.384	18	8.530	33	5.972	83	12.318
16	6.583	70	14.619	34	6.339	89	15.222
17	3.113	60	2.834	35	5.262	62	14.209
18	6.008	76	18.947	36	5.158	55	12.872

6. Establishing Mathematical Models

The mathematical models for the performance of the extrusion press were established based on the central composite rotatable design. The optimum combination of the four critical factors can be determined through optimum design. The detailed optimum design is described below.

The mathematical model for the performance of the extrusion press is formulated as:

4 4

$$Y_t = b_0 + \sum_{j=1} b_j x_j + \sum_{i<j} b_{ij} x_i x_j + \sum_{j=1} b_{jj} x_{jj},$$

In this equation, $t = 1, 2, 3$; $i = 1, 2, 3, 4$; $j = 1, 2, 3, 4$,

Where

Y_t is the value for performance indexes of the extrusion press, where Y_1, Y_2, and Y_3 are the values for the output per kilo-watt hour, the floatation rate, and the output per hour respectively; b is the multiple regression coefficients which are listed in Table 9; x is the coding values for the four different critical factors, where x_1, x_2, x_3, and x_4 are the coding values for the turning-speed, the screw pitch, the moisture content, and the number of holes respectively.

Table 9. Multiple Regression Coefficients

Regression Coefficients	Output per kilo-watt hour	Floatation rate	Output per hour
b_0	5.179	0.682	11.997
b_1	0.463	0.110	3.435
b_2	0.458	0.031	1.784
b_3	0.482	-0.067	-0.323
b_4	0.192	-0.200	0.303
b_{12}	0.008	0.009	-0.227
b_{13}	0.111	-0.002	-0.082
b_{14}	0.104	0.154	0.618
b_{23}	0.099	-0.001	0.032
b_{24}	-0.052	0.018	-0.359
b_{34}	0.023	-0.001	0.074
b_{11}	-0.333	-0.010	-1.168
b_{22}	-0.259	-0.160	-1.461
b_{33}	-0.048	-0.001	-0.503
b_{44}	-0.147	-0.018	-0.237

The calculations for x_1, x_2, x_3, and x_4 are shown in the following four equations, where s, p, m, and n are the values for the turning-speed, the screw pitch, the moisture content, and the number of holes respectively.

$x_1 = (s - 340)/100$,
$x_2 = (p - 18)/4$,
$x_3 = (m - 0.18)/0.03$,
$x_4 = (n - 4)/1$.

Consequently, the mathematical models for the three performance indexes of the extrusion press are:

$$Y_1 = 5.704 + 0.463x_1 + 0.458x_2 + 0.482x_3 + 0.192x_4 + 0.008x_1x_2 + 0.111x_1x_3 + 0.104x_1x_4 + 0.099x_2x_3 - 0.052x_2x_4 + 0.023x_3x_4 - 0.333x_1^2 - 0.259x_2^2 - 0.048x_3^2 - 0.147x_4^2;$$

$$Y_2 = 0.808 + 0.11x_1 + 0.031x_2 - 0.067x_3 - 0.2x_4 + 0.009x_1x_2 - 0.002x_1x_3 + 0.154x_1x_4 - 0.001x_2x_3 + 0.018x_2x_4 - 0.001x_3x_4 - 0.01x_1^2 - 0.16x_2^2 - 0.001x_3^2 - 0.018x_4^2;$$

$$Y_3 = 14.243 + 3.435x_1 + 1.784x_2 - 0.323x_3 + 0.303x_4 - 0.227x_1x_2 - 0.082x_1x_3 + 0.618x_1x_4 + 0.032x_2x_3 - 0.359x_2x_4 + 0.074x_3x_4 - 1.168x_1^2 - 1.461x_2^2 - 0.503x_3^2 - 0.237x_4^2.$$

In order to assess whether or not the three mathematical models have a goodness-of-fit, the analysis of variance was conducted. Table 10 lists the results of the analysis of variance. Based on the values of F_1 and F_2 shown in Table 10, it can be concluded that the mathematical models for the performance indexes of the extrusion press have a goodness-of-fit.

Table 10. Analysis of Variance

Name	Output per kwh	Floatation rate	Output per hour
S_T	27.833	3.051	538.965
S_r	23.684	2.610	495.26
S_l	4.149	0.441	43.705
S_f	2.406	0.250	27.784
S_e	1.743	0.192	15.922
$F_1 = (S_f/f_f) / (S_e/f_e)$	1.518	1.436	1.919
Significant level	0.25	0.25	0.1
$F_2 = (S_r/f_r) / (S_l/fl)$	8.562	8.364	16.998
Significant Level	0.01	0.01	0.01

7. Optimum Design

Having now established the mathematical models for extrusion press performance, it is very clear that the values of the four critical factors affect the performance of the extrusion press. The next step is to determine the values of the four critical factors in order to pursue the extrusion press's optimum performance indexes. This process is described as an optimum design. The output per kilo-watt hour is regarded as the most important performance index for the extrusion press. Pursuing the maximum output per kilo-watt hour is therefore the main target in developing the extrusion press. However, the other two performance indexes, the floatation rate and the output per hour also have to be taken into account in this optimum design. All constrained elements being considered are regarded as restriction conditions in this optimum design.

7.1 Determining Restriction Conditions

Based on the results of the single factorial experiments, the value ranges of the turning-speed, the screw pitch, the moisture content, and the number of holes have been determined. The turning-speed is ranged from 140 r/min to 540 r/min. The screw pitch is changed from 10 mm to 26 mm. The moisture content is varied from 12 percent to 24 percent. The number of holes ranges from 2 to 6. The floatation rate of granulated fish feed is the second most important performance index for the extrusion press. As described earlier, the value of the floatation rate in this optimum design must be more than or equal to 50 percent. In addition, although the target of the optimum design is to pursue the maximum output per kilo-watt hour, the maximum output per kilo-watt hour can not be equal to a relatively high output per hour. As a result, output per hour must be limited in this optimum design. Taking practical considerations into account, the value of the output per hour is set as more than or equal to 12 kg/h.

When all the elements are taken into account in this optimum design, the restriction conditions are:

(1) $-2 \le x_1 \le 2$;
(2) $-2 \le x_2 \le 2$;
(3) $-2 \le x_3 \le 2$;
(4) $-2 \le x_4 \le 2$;
(5) $-0.308 - 0.11x_1 - 0.031x_2 + 0.067x_3 + 0.2x_4 - 0.009x_1x_2 + 0.002x_1x_3 - 0.154x_1x_4 + 0.001x_2x_3 - 0.018x_2x_4 + 0.001x_3x_4 + 0.01x_1^2 + 0.16x_2^2 + 0.001x_3^2 + 0.018x_4^2 \le 0$;
(6) $-2.243 - 3.435x_1 - 1.784x_2 + 0.323x_3 - 0.303x_4 + 0.227x_1x_2 + 0.082x_1x_3 - 0.618x_1x_4 - 0.032x_2x_3 + 0.359x_2x_4 - 0.074x_3x_4 + 1.168x_1^2 + 1.461x_2^2 + 0.503x_3^2 + 0.237x_4^2 \le 0$.

7.2 Calculating the Optimum Results

In order to calculate accurate optimum results, a C-language computer program was constructed. The C-language program is shown in the Appendix. After the C-language program was run on a computer, the values for the extrusion press performance and the four critical factors of the extrusion press were calculated.

The values of the performance indexes of the extrusion press performance are shown below:

Output per kilo-watt hour = 7.398 kg/kwh;
Floatation rate = 59.30%;
Output per hour = 14.180 kg/h.

The values of the four critical factors are:

x_1 = 1.20, i.e., turning-speed = 460 r/min;
x_2 = 1.18, i.e., screw pitch = 21.54 mm;
x_3 = 2.00, i.e., moisture content = 24%;
x_4 = 1.00, i.e., number of holes = 5.

7.3 Verifying the Optimum Results

According to Taguchi's approach to quality by design, a confirmatory experiment is always run to verify the results (Logothetis and Wynn, 1989). If the results of the confirmation match the predicted values, the experiment has been confirmed. A successful confirmatory experiment may limit the possibilities of wrongly selecting the critical factors and the experimental design. Therefore, the optimum results for the extrusion press had to be verified by a confirmatory experiment. To do so, a new extrusion press was developed according to the optimum values of the four critical factors. Through experimenting with the new extrusion press, the quality performance indexes were measured, and the results are shown in Table 11. The errors between the calculated and actual performance indexes are less than 3 percent. It can be concluded that the experimental design and the optimum design are correct. The values of the four critical factors represent a true optimum factorial combination.

Table 11. Comparison of Calculated Values and Actual Values

Performance indexes	Calculated values	Actual values	Error
Output per kwh	7.398	7.590	2.53%
Floatation rate	59.30%	60.78%	2.44%

Output per hour	14.180	14.980	2.79%

8. Conclusions

Using experimental design has significantly reduced the time needed to develop the extrusion press and improved the quality of the new product. This clearly demonstrates that experimental design is an efficient technique for new product development. To ensure success when undertaking experimental design in new product development, there are some prerequisites which have to be taken into account. These include, for example, the need for a better understanding of customer requirements and expectations, a carefully planned design, and sound knowledge in the subject-matter. In addition, the economy and simplicity of experimental design should also be taken into account. It may be that a similar experimental design used for product development discussed in this article can also be used for developing other new products.

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Appendix

C-language program

```
#include<math.h>
#include<dos.h>
#include<stdio.h>
main()
{
float
f,a,a1,f1,y1,y2,y3,y4,f2,f3,x1,x2,x3,x4,h1,h2,h3,h4;
int i1,i2,i3,i4;
FILE *fp;fp=fopen("a:Zhang.dat","wt");
x1=-2.0;x2=-2.0;x3=-2.0;x4=-2.0;
f1=0.0
h1=0.01;h2=0.01;h3=0.01;h4=0.01;
for(i1=1;i1<=401;i1++)
{
x2=-2.0;
for(i2=1;i2<=401;i2++)
{
x3=-2.0;
for(i3=1;i3<=401;i3++)
{
x4=-2.0;
for(i4=1;i4<=401;i4++)
{
f=0.0;
a=5.704+0.463*x1+0.458*x2+0.482*x3+0.192*x4+0.008*x1*x
2;
a1=a+0.111*x1*x3+0.104*x1*x4+0.099*x2*x3-
0.052*x2*x4+0.023*x3*x4;
f=a1-0.333*x1*x1-0.259*x2*x2-0.048*x3*x3-0.147*x4*x4;
```

```
if(fabs(f)>=f1)
{
f2=-2.243-3.435*x1-1.784*x2+0.323*x3-
0.303*x4+0.227*x1*x2;
f2=f2+0.082*x1*x3-0.618*x1*x4-0.032*x2*x3+0.359*x2*x4-
0.074*x3*x4;
f2=f2+1.168*x1*x1+1.461*x2*x2+0.503*x3*x3+0.237*x4*x4;
if(f2<=0)
{
f3=-0.308-0.11*x1-0.031*x2+0.067*x3+0.2*x4-
0.009*x1*x2;
f3=f3+0.002*x1*x3-0.154*x1*x4+0.001*x2*x3-0.018*x2*x4;
f3=f3+0.001*x3*x4+0.01*x1*x1+0.16*x2*x2+0.001*x3*x3+
0.018*x4*x4;
if(f3<=0)
{f1=fabs(f);printf("%f\n",f1);y1=x1;y2=x2;y3=x3;y4=x4;
}
}
}
x4=x4+h4;
}
x3=x3+h3;
}
x2=x2+h2;
}
x1=x1+h1;
}
fprintf(fp,"qq= %f %f %f y1= %f y2= %f y3= %f y4=
%f\n",f1,f2,f3,y1,y2,y3,y4);
return(0);
}
```